Physics Based Model for Simulating the Dynamics of Tower Cranes

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1 Introduction and Motivation

The goal of the research is to increase the understanding of dynamic behaviors during the crane operation, and develops computer-aided methods to improve the training of crane operators. There are approximately 125,000 cranes in operation today in the construction industry, responsible for major portion of erection activities. Unfortunately, many accidents occur every year in the U.S. and other countries related to the operation of cranes in construction sites. For example on November 28, 1989 a tower crane collapse during the construction of a building in San Francisco killing four construction workers, one civilian and injuring 28. According to the statistics from Occupational Safety Health Administration (OSHA), there were 137 crane-related fatalities from 1992 to 2001 in the US. A well-known internet website that keeps track of crane-related accidents (craneaccidents.com), reports 516 accidents and 277 fatalities from 2000 to 2002. These statistics show that even though many measures have been taken to decrease the number of crane-related accidents (Braam, 2002), the number of crane related accidents is still very large. It is important to recognize that each construction related fatality is not only a great human loss but also increases the costs of insurance, lawsuits, and the construction budget due to delay of a project (Paulson 1992).

Since improper operation is the main reason causing the crane accidents, it is worthwhile to increase research efforts to develop more effective methods to facilitate crane operations. One of the major challenges for the crane operation is to control the swing of the crane cable, which requires intensive training for the operators. However, training to control the dynamic behavior of the crane is very danger and difficult to be performed in actual construction sites. Therefore, the research is focusing on building a physics based model to simulate the dynamic behavior of tower cranes, and applies the model to assist the training of crane operators.

Because it is very difficult to attach the hook on top of the center of gravity of each piece, vibrations are often introduced in the object. In addition, construction materials are often very large and heavy, which are likely to experience significant inertia forces caused by changing velocity (accelerations) during crane motions. Since typically there is very little damping in the dynamic system, these vibrations can have large amplitudes and can last many seconds or minutes. These vibrations can be very dangerous to personnel located in the proximity of structural elements or other components being lifted. When reaching the final position, the structural element must be completely resting (zero motion) to allow onsite crews bolting onto the structure. Therefore, operators need to be trained to manipulate the crane in order to minimize vibration of heavy elements when close to personnel and when the piece is arriving to its final position.

A powerful visualization interface for displaying crane dynamic behavior is implemented in the research. The system builds a 3D virtual construction site containing a tower crane, constructing structure, and site layout, and renders the view from the cabin window which allows users to experience the operators' position. The system allows users to visualize the effects of different crane motions on the vibration of the pieces being lifted. Because many tower cranes in the construction sites are installed a camera below the jib to help operators see the views which are unclear from the cabin window, the system also provides the camera view for the users. Operators are able to learn to operate a tower crane safely and efficiently using limited information from the window view of the cabin and the camera view.

The result of the research allows the development of an effective training program for construction operators. Using the physics based model to simulate the crane motion, the training system will help new operators to learn how to control crane cable within maximum safety vibration. Because the training is held in a virtual environment, the operators can be trained to handle many critical and dangerous situations which are difficult to be trained in current training programs. Hence, the simulation system will facilitate the new operators to build up the solid experience and skill during the training, and result in the improvement of construction productivity and safety.

2 Previous Research

Cosntruction cranes were studied for years in a wide range of aspects. Tam et al. (2001) used the model developed by Zhang et al together with genetic algorithms to predict hoisting times. Leung and Tam (1999) collected data from three projects in Hong Kong to develop an empirical model to assess hoisting times of tower cranes based on twenty variables. In their work they computed "supply" and "return" times as a linear combination of the variables that proved to be statistically significant from the data collected. Their work has been more recently extended using nonlinear neural network models. One aspect that is common in all of the previous investigations is that hoisting times can been computed primarily based on the loading and unloading positions and not on the simulation of actual paths. One of the few investigations that has considered paths is Bechtel's ALPS system (Bennet et al. 1994) which was designed to assist in heavy lifting operations. The system allowed the user to select the crane from various possible rigging assemblies (wire rope slings, shackles, links, pins lifting beams, etc) to simulate the lift in three dimensions. Although the system, which was primarily aimed to be used for specific heavy lifts and not in assisting full erection of construction projects, considered the actual crane motions and load paths, crane motions were provided manually by the user and not computed by the system. The system constituted one of the first efforts to plan and visualize crane lifting operations.

The other important research has been done to provide visualization capabilities for crane operations. For example, Lipman and Reed (2000, 2003) developed 3D crane models using Virtual Reality Modeling Language (VRML), which is an open standard of constructing a 3D world in the Internet. The crane model developed by these investigators can be manipulated over the internet using VRML browsers to complete one or more tasks. Chui (2000) also used VRML to visualize tower crane operations to install curtain walls in a virtual world. These researchers have demonstrated the great potential of visualizing construction operation by virtual reality technology. However, emphasis was on visualization and all crane motions were still done manually. In other words the system did not had "intelligence" to tell the crane how it should move to accomplish a given task.

Recently there has been also an important effort focusing on equipment aimed at construction automation. RoboCrane was developed at the National Institute of Standards and Technology (NIST) for heavy manufacturing or construction tasks such as lifting and positioning heavy loads as well as for manipulation of tools and parts for assembly, welding, cutting, and surface finishing (Amatucci et al. 1997; Bostelman et al. 1994, 2001). Although RoboCrane has explored innovative ways for using computers to automate the construction tasks, it is still far from being applied to common construction sites and difficult to replace the tower cranes in the near future. Because tower cranes are still the most commonly used erection equipment in current construction projects, the proposed research is based on improving the capabilities of existing tower cranes in order to achieve fully construction automation in the future as opposed to the development of new lifting equipment.

Although a great amount of research efforts have been done focusing on construction cranes, to the best of our knowledge, none of the previous studies consider the dynamics of crane cables. The research add the consideration of dynamics behavior during the crane motions, and focuses on developing a general physics-based crane model which allow to be used for educational or practical purposes.

3 Physics Based Crane Model

This research constructs a physics-based model of a tower crane by treating the crane as a four degrees-of-freedom (dof) robot. Combined with the rigging and piece, the robot translates to a dynamic system with a total of eight degrees of freedoms. According to the physics characteristics of the crane cable, the research will derive the equations of motion and develop an equation solver to solve these equations in each time step during crane operations. In the case of tower cranes, the four dofs that can be controlled by crane operators and other construction personnel are (1) jib rotation, (2) trolley radial movement, (3) hook (block) lifting and lowering, and (4) hook rotation with respect to the cable. The other four dynamics dofs are determined by the dynamic of the cable, block/hook, rigging and elements being suspended from the trolley. They are including (1) the swing of the cable parallel to the jib, (2) the swing of the cable perpendicular to the jib, (3) the swing of the rigging with respect to the cable in a plane parallel to the jib, and (4) the swing of the rigging with respect to the cable in a plane perpendicular to the jib (see figure 1). The four dynamic dofs are used to construct the equations of motion of the dynamic system. The former four dofs cause the external force to the system when they are moving. Therefore, the external force terms in equations of motions can be calculated from the four dofs.

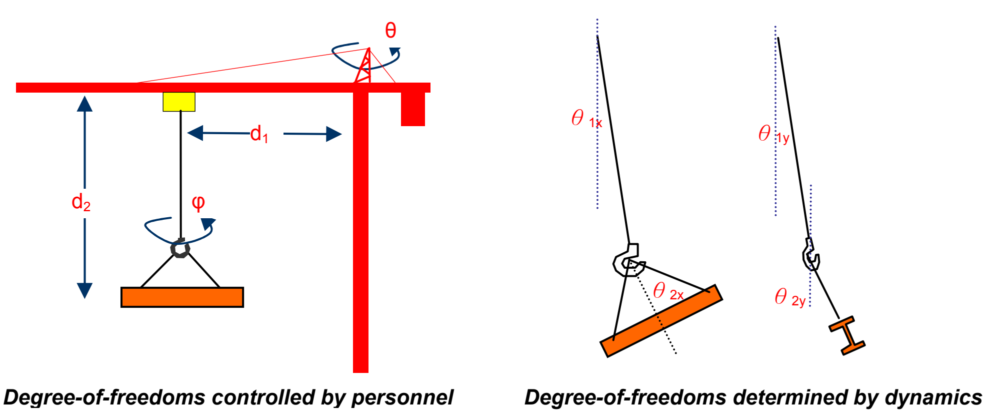

Fig 1 Eight degree-of-freedom tower crane

As shown in figure 1, θ is denoted as the rotational angle of the jib, d_1 is denoted as the distance between the crane tower and trolley, and d_2 is denoted as cable length for rigging the object. In addition, we denote φ as hook rotation by z axis (horizontal rotation). In most tower cranes, the hooks are allowed to rotate for completing various construction tasks. This dof is usually controlled by onsite personnel when the rigging structural element approaching its target position.

$\dot{\theta}$ and $\ddot{\theta}$ represent the rotational angular velocity and angular acceleration respectively. $\dot{d}_1$ and $\ddot{d}_1$ are velocity and acceleration of trolley movement; $\dot{d}_2$ and $\ddot{d}_2$ are velocity and acceleration of cable lifting or lowering speed.

The cable mechanism is simulated as a pendulum system. The reasons are: 1) the mass of construction elements are much bigger than the mass of cable and lead to the dynamics behavior similar to a pendulum; 2) in normal tower crane operation, the vibration amplitude θ is relative small, meeting the assumption of pendulum theory.

The tower crane cable can be modeled by a 2-dofs pendulum system in both X and Y directions. In each direction, the system is composed of two sections: one is from trolley to hook and the other is from hook to the rigged object. Hence, we denote θ_{1x} and θ_{2x} as the 2 dofs pendulum system in x direction, and θ_{1y} and θ_{2y} as in y direction.

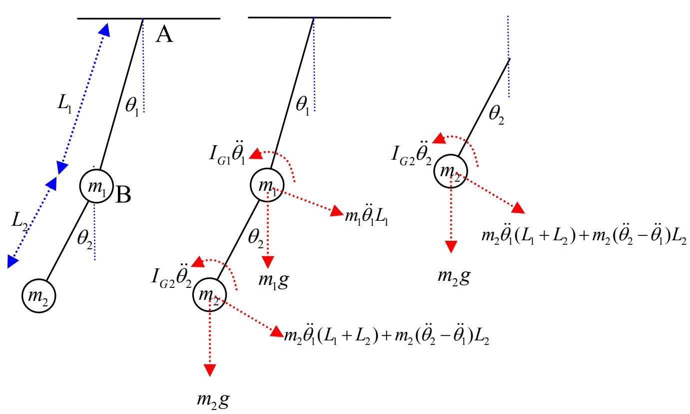

Fig 2 Dynamic equilibrium

Using the eight parameters, we are able to describe tower crane behavior completely. The following will develop the motion equation of a tower crane.

Here we start from deriving the 2-dof undamped motion systems in tower crane cable. The format of 2DOF equation of motion is,

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}+\begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad (1)$$

For simplifying the process, we consider one direction first and generalize to the 3D space. To get the 2-dof equation of motion, we need to include two equations of dynamic equilibrium. First, we take free body in point A, the sum of moment in A should be zero. Hence,

$$\sum M_A = 0$$

$$I_{G1}\ddot{\theta}_1 + m_1\ddot{\theta}_1 L_1^{\ 2} + k_1\theta_1 + m_1 g L_1 \sin\theta_1 + I_{G2}\ddot{\theta}_2 + m_2\ddot{\theta}_1(L_1+L_2)^2 + m_2(\ddot{\theta}_2-\ddot{\theta}_1)L_2(L_1+L_2) + k_2(\theta_2-\theta_1) + m_2 g(L_1\sin\theta_1 + L_2\sin\theta_2) = 0$$

……… (2)

Similarly, take free body in point B, sum of moment in B is zero too.

$$\sum M_B = 0$$

$$I_{G2}\ddot{\theta}_2 + m_2((L_1+L_2)\ddot{\theta}_1 + L_2(\ddot{\theta}_2-\ddot{\theta}_1))L_2 + k_2(\theta_2-\theta_1) + m_2 g L_2 \sin\theta_2 = 0 \qquad (3)$$

Reorganize all items to matrix format, and obtain mass and stiffness matrices.

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} I_{G1} + (m_1+m_2)L_1^{\ 2} & m_2 L_2 L_1 \\ m_2 L_1 L_2 & I_{G2} + m_2 L_2^{\ 2} \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} = \begin{bmatrix} k_1 + k_2 + (m_1+m_2)gL_1 & 0 \\ -k_2 & k_2 + m_2 g L_2 \end{bmatrix} \qquad (5)$$

To solve the motion equation, we need to decompose the 2-dof system into two single degree of freedom systems. To simplify the denotation, rewriting equation 1 as a matrix format:

$$M\ddot{\theta} + K\theta = 0 \tag{6}$$

Where M is mass matrix, K is stiffness matrix (spring term), and $\theta = [\theta_1 \quad \theta_2]^t$ is displacement matrix

To solve the 2-dof equation, we need to normalize the M and K matrices as following steps:

1. Find eigenvalue and eigenvector. Eigenvector is a 2x2 matrix as follows:

$$\phi = \begin{pmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{pmatrix} \tag{7}$$

2. Define q matrix. Any set of N independent vectors can be used as a basis for representing any other vector of order N. Therefore, θ can be represented by q as follows:

$$\theta = \phi q = \begin{bmatrix} \phi_{11}q_1 + \phi_{12}q_2 \\ \phi_{21}q_1 + \phi_{22}q_2 \end{bmatrix} \tag{8}$$

Equation 6 can be rewritten as $M\phi\ddot{q} + K\phi q = 0$.

3. Get diagonal matrices

Premultiplying ϕ^t to equation 8, diagonal matrices, *M'* and *K* will be obtained.

$$\begin{aligned} &\phi^t M\phi\ddot{q} + \phi^t K\phi q = 0 \\ &M'\ddot{q} + K'q = 0 \end{aligned} \tag{9}$$

Because M' and K' are diagonal matrices, we are able to decompose the 2-dof system into two ordinary differential equations as follow:

$$\begin{aligned} &M'_{11}\ddot{q}_1 + K'_{11}q_1 = 0 \\ &M'_{22}\ddot{q}_2 + K'_{22}q_2 = 0 \end{aligned} \tag{10}$$

Where M'_{ij} is ij item in *M'* matrix and K'_{ij} is ij item in *K'* matrix

External forces of the dynamics system are determined by the motions of the tower crane. According to Newton's second law, we can transfer acceleration of trolley movement and jib rotation to external forces. As shown in Fig 3, we denote acceleration of trolley movement as $\ddot{d}$ and angular acceleration of jib as $\ddot{\theta}$.

Denote $P_{1x}(t)$ is the time history of external force in x direction applied in hook and P_{2x} (t) is the time history of hanged object. W_x represents the wind effect in x direction. Here we ignore the wind effect on the hook, but only consider wind force applied to the object. Considering the acceleration of trolley movement and centrifugal force from rotation:

$$\begin{aligned} &P_{1x}(t) = -m_1(-d_1\dot{\theta}^2 + a) \\ &P_{2x}(t) = -m_2(-d_1\dot{\theta}^2 + a) + W_x \end{aligned} \tag{11}$$

P_{1y} (t) is the time history of external force in y direction applied to hook, and P_{1y} (t) is applied to object. W_y is the wind effect in y direction. Considering the wind effect, angular acceleration of tower crane rotation, and trolley movement, we can obtain external force as follows:

$$
\begin{aligned}
P_{1y}(t) &= -m_1 d_1 \ddot{\theta} \\
P_{2y}(t) &= -m_2 d_1 \ddot{\theta} + W_y
\end{aligned}
\tag{12}
$$

Now we extend free vibration motion equation (equation 1) by external forces, and consider the motion in X direction and Y direction separately. M_x and K_x represent the mass and stiffness matrix in X direction, and M_y, K_y represent them in y direction. Therefore, we can derive equation 13 as follows:

$$
\begin{aligned}
&M_x \ddot{\theta} + K_x \theta = P_x \quad \text{Where } P_x = [P_{1x}(t) \quad P_{2x}(t)]^t \\
&M_y \ddot{\theta} + K_y \theta = P_y \quad \text{Where } P_y = [P_{1y}(t) \quad P_{2y}(t)]^t
\end{aligned}
\tag{13}
$$

Following the decomposing procedure in previous section, we can represent the equations with diagonal mass and stiffness matrices with external forces.

$$
\begin{aligned}
M_x' \ddot{q}_x + K_x' q_x &= \phi_x^t P_x = P_x' \\
M_y' \ddot{q}_y + K_y' q_y &= \phi_y^t P_y = P_y'
\end{aligned}
\tag{14}
$$

To summarize previous equations, solving the following ordinary differential equations, the dynamics of a crane cable will be obtained.

$$
\begin{aligned}
M_{11x}\ddot{q}_{1x} + K_{11x} q_{1x} &= \phi_{11x} P_{1x} + \phi_{21x} P_{2x} \\
M_{22x}\ddot{q}_{2x} + K_{22x} q_{2x} &= \phi_{12x} P_{1x} + \phi_{22x} P_{2x} \\
M_{11y}\ddot{q}_{1y} + K_{11y} q_{1y} &= \phi_{11y} P_{1y} + \phi_{21y} P_{2y} \\
M_{22y}\ddot{q}_{2y} + K_{22y} q_{2y} &= \phi_{12y} P_{1y} + \phi_{22y} P_{2y}
\end{aligned}
\tag{15}
$$

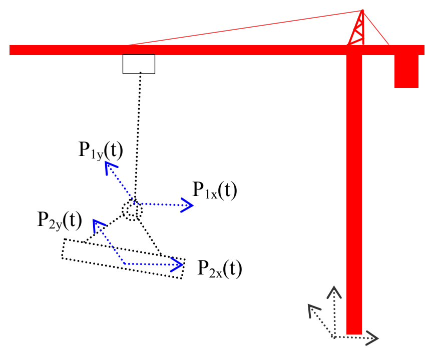

Fig 3. External forces

The research introduces Caughey damping to simulate decay of amplitude. Here we define ξ as damping ratio. If having stiffness constant k and mass m, we can get damping constant c.

$$
c = 2\sqrt{km} \cdot \xi \tag{16}
$$

4 Implementation of the equation solver

The real time motion equation solver for a construction tower crane developed in the research can calculate the swing of the crane cable by the parameters of crane operations and environmental force. Analytical solution for the following equations is usually impossible. The research used numerical time-stepping method for iteration of differential equations. The following equations need to be solved:

$$
\begin{bmatrix} I_{G1x} + (m_1+m_2)L_1(t)^2 & m_2 L_2 L_1(t) \\ m_2 L_1(t) L_2 & I_{G2x} + m_2 L_2^2 \end{bmatrix}
\begin{bmatrix} \ddot{\theta}_{x1}(t) \\ \ddot{\theta}_{x2}(t) \end{bmatrix}
+ \begin{bmatrix} c_{11x} & c_{12x} \\ c_{21x} & c_{22x} \end{bmatrix}
\begin{bmatrix} \dot{\theta}_{x1}(t) \\ \dot{\theta}_{x2}(t) \end{bmatrix}
+ \begin{bmatrix} k_1 + k_2 + (m_1+m_2) g L_1(t) & 0 \\ -k_2 & k_2 + m_2 g L_2 \end{bmatrix}
\begin{bmatrix} \theta_{x1}(t) \\ \theta_{x2}(t) \end{bmatrix}
= \begin{bmatrix} -m_1(d_1(t)\omega(t)^2 + a(t)) \\ -m_2(d_1(t)\omega(t)^2) + W_x(t) \end{bmatrix}
\tag{17}
$$

$$
\begin{bmatrix} I_{G1y} + (m_1+m_2)L_1(t)^2 & m_2 L_2 L_1(t) \\ m_2 L_1(t) L_2 & I_{G2y} + m_2 L_2^2 \end{bmatrix}
\begin{bmatrix} \ddot{\theta}_{y1}(t) \\ \ddot{\theta}_{y2}(t) \end{bmatrix}
+ \begin{bmatrix} c_{11y} & c_{12y} \\ c_{21y} & c_{22y} \end{bmatrix}
\begin{bmatrix} \dot{\theta}_{y1}(t) \\ \dot{\theta}_{y2}(t) \end{bmatrix}
+ \begin{bmatrix} k_1 + k_2 + (m_1+m_2) g L_1(t) & 0 \\ -k_2 & k_2 + m_2 g L_2 \end{bmatrix}
\begin{bmatrix} \theta_{y1}(t) \\ \theta_{y2}(t) \end{bmatrix}
= \begin{bmatrix} -m_1 d_1(t)\alpha(t)^2 \\ -m_2 d_1(t)\alpha(t)^2 + W_y(t) \end{bmatrix}
\tag{18}
$$

The equations 17 and 18 show the motion equations are changing in each time step. In other words, the solver has to calculate and reconstruct the mass matrices, and stiffness matrices, damping matrices, and external force matrices in each time increment.

The next step is to decouple the dynamic system. Eigenvectors φ will be calculated by using inverse iteration method. Using the eigenvectors φ can transfer the dynamic system orthogonal coordinate so that diagonal mass matrix $[M]_x$ or $[M]_y$ diagonal stuffiness matrix $[K]_x$ or $[K]_y$, and respective external force $[P]_x$ or $[P]_y$ can be obtained.

After decomposing motion system, the solver obtains four developed ordinary differential equations (ODEs), and will employ Newmark's method to solve the equations. The four equations represent the dynamic system of the crane cable in 1^{st} mode and 2^{nd} mode in x and y directions respectively. Finally the solver will transform the 1^{st} and 2^{nd} mode dynamic behavior to the angles of the cable swings. The workflow of entire solving procedure is shown in figure 4.

4.1 ODE solver

The ODE solver needs to solve a single-degree-of-freedom problem of each time step. The equation of motion is:

$$m(t)\ddot{u}(t) + c(t)\dot{u}(t) + k(t)u(t) = p(t)$$

During time step t_i, the solver has to compute the constant terms of equations of motion, including $m(t_i)$, $c(t_i)$, $k(t_i)$, $p(t_i)$, $u(t_i)$, $\dot{u}(t_i)$, Δt, and find the displacement and velocity of next time step, including $\dot{u}(t_{i+1})$ and $u(t_{i+1})$.

In the research, Newmark's method, a time-step method, is employed based on the following equations.

$$\dot{u}(t_{i+1}) = \dot{u}(t_i) + [(1-\gamma)\Delta t]\ddot{u}(t_i) + (\gamma\Delta t)\ddot{u}(t_{i+1})$$
$$u(t_{i+1}) = u(t_i) + (\Delta t)\dot{u}(t_i) + [(0.5-\beta(\Delta t)^2]\ddot{u}(t_{i+1}) + [\beta(\Delta t)^2]\ddot{u}(t_{i+1})$$

The parameter γ and β define the variation of acceleration over a time step and determined the stability and accuracy characteristics of the method. Typical section for $\gamma = 0.5$, and $1/6 \le \beta \le 1/4$ is satisfactory in most situations. Because assuming the acceleration during t_i to t_{i+1} remains constant, the research chooses $\gamma = 0.5$ and $\beta = 0.25$ (Chopra 2000).

The procedure of Newmark's method is as follows:

Step 1. $\ddot{u}(t_i) = (p(t_i) - c\dot{u}(t_i) - k(t_i)u(t_i)) / m(t_i)$

Step 2. $\hat{k} = k(t_i) + \dfrac{\gamma}{\beta\Delta t}c(t_i) + \dfrac{\gamma}{\beta(\Delta t)^2}m(t_i)$

Step 3. $a = \dfrac{1}{\beta\Delta t}m(t_i) + \dfrac{\gamma}{\beta}c(t_i)$ and

$b = \dfrac{1}{2\beta}m(t_i) + \Delta t_i(\dfrac{\gamma}{2\beta} - 1)c$

Step 4. $\Delta\hat{p} = \Delta p(t_i) + a\dot{u}(t_i) + b\ddot{u}(t_i)$

Step 5. $\Delta u = \Delta\hat{p} / \hat{k}$

Step 6. $\Delta\dot{u} = \dfrac{\gamma}{\beta\Delta t}\Delta u - \dfrac{\gamma}{\beta}\dot{u}(t_i) + \Delta t(1 - \dfrac{\gamma}{2\beta})\ddot{u}(t_i)$

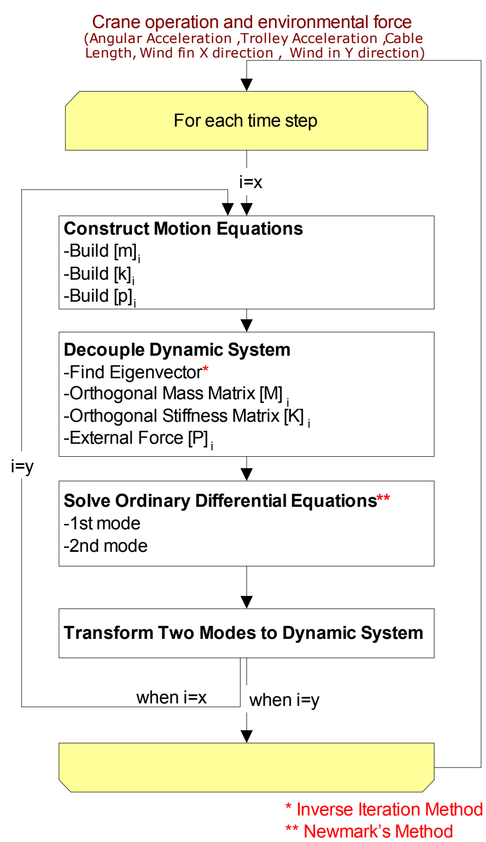

Fig 4. Workflow of Solving

Step 7. update $u(t_{i+1}) = u(t_i) + \Delta u$, $\dot{u}(t_{i+1}) = \dot{u}(t_i) + \Delta \dot{u}$

4.2 Eigenvector solver

The eigenvalue problem, resulted from the free vibration of an undamped system can be represented as the mathematical format $Kq = \lambda Mq$. Inverse iteration method is applied to find eigenvector of the given mass matrix m and stiffness matrix k. The procedure is as follows:

Step 1. Initialized eigenvector x_1 and eigenvalue λ_1

Step 2. Solve next approximation of eigenvector $\bar{x}_{j+1} = K^{-1}Mx_j$

Step 3. Rayleigh Quotient to approximate the eigenvalue $\lambda^{(j+1)} = \dfrac{\bar{x}_{j+1}^T Mx_j}{\bar{x}_{j+1}^T M\bar{x}_{j+1}}$

Step 4. Mass normalize $x_{j+1} = \dfrac{\bar{x}_{j+1}}{(\bar{x}_{j+1}^T M\bar{x}_{j+1})^{1/2}}$

Step 5. if $\left|\lambda^{j+1} - \lambda^j\right| / \lambda^{j+1} < tolerance$ return $\bar{x}_{j+1}$ otherwise step 2.

The second eigenvector can be found by spectrum shift. After shifting, the equation becomes $(K - \mu M)q = \hat{\lambda} Mq$ where $\lambda = \hat{\lambda} + \mu$, which can be solved by the procedure above. Implementation and testing

4.3 Implementation and Testing

The research implements the equation solver to calculate dynamic behavior of crane cable in each time step. The computer system of physics-based crane model is implemented in Mircrosoft .NET environment (Prosise 2002), and can be executed in most personal computers. The equation solver is written by c#, an object oriented language particularly good to develop projects in .NET platform (Liberty 2003). A class, DynaCrane, is developed for solving the 2 dof ODE problem during the crane operation. DynaCrane take the inherit advantage in object oriented language, encapsulating trivial calculation in private methods and only allow others to access via public methods. The characteristics of encapsulation make the codes easier to be resued, and facilitate the future development for education or simulation.

Using openGL (Woo et al 1997), one of the most common used graphics language, a powerful visualization interface for displaying the dynamic behavior of the crane is developed in this research. As shown in figure 2, the system builds a 3D virtual construction site containing a tower crane, constructing structure, and site layout, and renders the view from the cabin window which allows users to experience the operators' position. The system allows users to visualize the effects of different crane motions on the vibration of the pieces being lifted, and offers a number of virtual cameras to provide further visualization of erection operations. The system can be used as a crane operation simulation where operators can learn to understand the relation between crane movement and vibrations of elements being erected.

Several testing prove the physics-based model is able to generate crane motions close to the observation in actual construction sites. When the trolley moves, Newton's first law keeps the rigging element remains in original position and results in an initial acceleration in opposite direction of trolley movement. When the crane rotates, other than the force being introduced from the initial acceleration, centrifugal force will move the element away from the tower of the crane. When wind force is introduced, crane cable swings against the wind direction, and vibrates freely after wind stops. The following figures show the two clips in the animation of physics-base crane model.

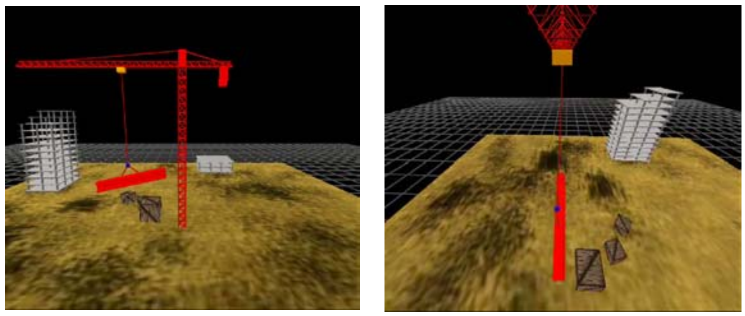

Figure 5 Snap shots of the visualization the physics-based crane model

5 Using Physics Based Crane Model for Educational Purposes

This research successfully constructs a crane model which allows generating realistic dynamic behavior of a tower crane during operation. The real time solver of the motion equation is developed and proved the feasibility for the real time visualization purposes. The animation of cranes vibration generated by the model is close to the observation in actual construction site.

The physics-based model can be further developed for various educational purposes, such as training program for crane operators, or course material for university students. In order to achieve this goal the following activities can be further developed:

- Development of well-thought and easy to follow step-by-step lessons for training crane operators. In the lessons, the new operators start from basic lessons such as manipulation of the tower crane, reading the load chart, and parking or tighten the crane, etc. After the basic lessons, simulation lesson will help the new operator to be familiar with the equipment. The trainees have to learn how to operate a tower crane considering both safety and efficiency. Students could then compare their paths and motions to those generated by the computer. Because the training is held in a virtual environment, the operators can be safely trained to handle many critical and dangerous situations that are difficult to be trained in current training program.
- Design and implement a construction simulation system for the undergraduate or graduate students to learn construction scheduling and management. Students are able to input different site layouts, crane locations and erection sequences, and "see" the erection processes in the computer immediately.
- Development of the lessons for the integration between design and construction. Traditionally structural design classes discuss very little about constructability during the design phase. However, the trend of design build and fast-track construction requires the designers to consider the construction issues for benefiting the overall project. The system can demonstrate the effect of decisions regarding the location of splices, the benefits of pre-assembly, and of connection that facilitate crane operations. The simulation system will help the designers to obtain designs of projects that are faster and

safer to erect. Ultimately, with this type of tools designers will have the ability to consider both design and construction issues during the design phase.

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